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(54) Title: MODULAR APPARATUS FOR REGULATING THE HARMONICS OF CURRENT DRAWN FROM POWER LINES

(57) Abstract

Modular apparatus for regulating the harmonics of current drawn from power lines by electric equipment, comprising a first rectifier circuit module, consisting of an array of rectifying diodes; a second Switch and Controller Assembly (SCA) module, which comprises a power switch and controller and their interconnections; an input inductor for filtering the current drawn from the rectifier module; and an output capacitor, for filtering the output voltage ripple at the load. The inlet of the rectifier is connected to the power line and an outlet of the rectifier module is connected to the SCA. The inlet of said SCA is connected to the rectifier, via an inductor and the outlet of said SCA is connected to the output capacitor. The inlet of the inductor is connected to the rectifier, the outlet of the inductor is connected to the inlet of said SCA, and the capacitor is connected in parallel with the load.

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MODULAR APPARATUS FOR REGULATING THE HARMONICS OF CURRENT DRAWN FROM POWER LINES

Field of the Invention

The present invention relates to the field of power electronics. More particularly, the invention relates to a method for regulating the harmonics of current drawn from power lines, by electric equipment, using modular design and construction techniques.

Background of the Invention

The art has devoted a considerable effort to the problem of shaping the current amplitude and phase drawn from the power line, loaded by electric equipment. Switch Mode and Resonant Converters are widely used for DC-DC (Direct Current - Direct Current), DC-AC (Direct Current - Alternate Current), AC-DC and AC-AC conversion. In some applications, the purpose of power conversion is to shape the current at the input of the converter. For example, an input power stage known in the art as an Active Power Factor Correction (APFC) circuit, the function of the converter is to insure that the AC current supplied from the source (power line) will appear in almost the same shape and phase as the source voltage. Thus, a Power Factor (PF) of unity is obtained.

The need for APFC stages is driven by the worldwide concern about the quality of power supplies. Generally, poor power factors results is several problems, comprising low efficiency of power transmission, interference to normal operation of other units connected to the same power line, as well as distortion of the voltage shape. Voluntary and mandatory standards that restrict the acceptable level of the current harmonics generated by the loading equipment, have been adopted by many countries, so as to maintain high power quality.

Another advantage of APFC is increased power levels that may be drawn from the power line. Looking at the spectral components of the current without APFC, only the fundamental (first) harmonic component contributes to the real load power. The root mean square (rms) magnitude of the current is increased beyond the level of the fundamental magnitude, as a result of higher order harmonics. Since the operation of protection elements, such as fuses and circuit breakers, is affected by the rms current, increased rms level limits the maximum power level that may be drawn from the line. Using electric equipment with APFC enables the rms current level to be equal to the level of the fundamental harmonic. Hence, the power that may be drawn from the line may reach its maximum theoretical level.

From the above description, it is clear that the need for APFC is wide spread, and economic implementation of APFC circuitry is of prime importance. Moreover, the cost of APFC circuits is of great concern considering the fact that APFC cost is an add-on expense to the functionality of the original equipment. As a result, APFC units should be constructed using methods that are economic during production, and are easy to integrate in any existing equipment.

Some known methods for physical implementation of APFC stages, sub-circuits, which are part of the electrical circuit of the (loading) equipment are used. In this case, the designer of this equipment engages passive and active components, as well as Integrated Circuits (ICs) to construct the desired APFC stage. Normally, designs that involve many components suffer from several drawbacks, like relatively high cost and low reliability. Moreover, these designs require many wiring connections, resulting in relatively high susceptibility to Electro-Magnetic Interference (EMI), "ground noise" and other engineering disadvantages.

Other construction methods comprise one "block" (APFC block) that includes all the components and circuitry of an APFC stage. This implementation provides functional solution to the design problem from the electrical aspect, but still requires satisfactory heat dissipation design. Still, a separate APFC unit should be normally purchased from another manufacturer (which is more skilled in this kind of products), leading to higher cost. Another disadvantage is the fact that this realization is not compatible with IC technology, which normally has the benefit of low cost in mass production. Further problem using APFC block is the fact that in this implementation, all heat dissipating components, such as the main switch, diodes and the inductor are close to each other. This proximity leads to a severe heat dissipation problem, which may limit the power handling capability of such module. Additionally, because of this component proximity, EMI restrictions require heavy snubbing, shielding and filtering, all leading to complexity, higher cost and lower efficiency.

U.S. Patent 5,530,635 to Yashiro describes a power supply divided into a noise filtering module, one or more power factor and harmonic correction modules, one or more DC-DC converter modules and a backup power supply for the power converter modules. Each module may optionally be combined so as to construct a desirable power supply according to various required specifications. However, this construction lacks simplicity, since it is not realizable using IC technology and in addition is not advantageous with respect to optimal heat dissipation.

U.S. Patent 5,047,912 to Pelly describes a modular four terminal realization of APFC stages. The control circuit comprises a signal differentiator, for generation of a reference signal to the feedback loop of the circuit. Differentiators are known in their extreme noise sensitivity, which may corrupt the output signal. Switching circuits such as Pulse Width Modulation (PWM) Boost converters, which are characterized by

high frequency noise injection, are also problematic to use. Another problem arises from this patent is the reference feedback signal is driven from the line voltage, which contains additive noise that distorts the shape of the desired controlled line current.

A different problem, which is not solved by U.S. Patent 5,047,912 is the generation of a local power supply (from the line voltage) for the control circuitry. High power APFC stages requires local power supplies of several watts. Using an external power supply for this purpose requires additional circuitry and pin connection, which increase cost. Another approach is to drive the power supply from a voltage divider from of the output voltage, or from the voltage across the main switch. This approach is extremely inefficient, especially in case of high power applications.

Another disadvantage of U.S. Patent 5,047,912 is the need for fast diodes for its input rectifier, due to the fact that the line rectifier in this patent is locate after the input inductor. At this point, the signals are switching frequency signals that requires fast rectifier diodes, so as to eliminate high power loss. Using fast diodes introduces higher switching noise, as well as higher cost (since such diodes are more expensive).

All the methods described above have not yet provided satisfactory solutions to the task of constructing simple, low-cost, modular APFC stages.

It is an object of the invention to provide an APFC unit, for regulating the harmonics of power line current, that comprise low number of components.

It is another object of the invention to provide a compact, low cost APFC unit.

It is another object of the invention to provide a compact APFC unit, with a minimal amount of interconnections.

It is still another object of the invention to provide an APFC unit with efficient local power supply feeding switching and control circuit.

It is yet another object of the invention to provide an APFC unit which is compatible with IC technology.

It is yet another object of the invention to provide an APFC unit which do not comprise signal differentiation, while overcome the drawbacks of the prior art.

Other purposes and advantages of the invention will appear as the description proceeds.

Summary of the Invention

The invention is directed to construction of a modular apparatus for regulating the harmonics of current drawn from power lines by electric equipment. This apparatus comprises a rectifier circuit module with optional high frequency filtering capacitor, a Switch and Controller Assembly (SCA) module, which comprising all semiconductor power devices control circuitry and their interconnections, an input inductor, smoothing the current drawn from the rectifier module and an output capacitor, filtering the output voltage.

Preferably, the main power factor correction operation is carried out by the SCA module. Correction is obtained by a high frequency controlled switching of the input rectified voltage. Further rectification is carried out by a high frequency rectifier diode connected in series with the SCA outlet. The control circuit samples both the input current and the output voltage

of the SCA and controls the switching transistor accordingly by an inherent pulse width modulator responsive to the control signal. The control circuit is fed by a power supply via an inlet in the SCA module. Preferably, optional soft switching is obtained using an integrated turn-on snubber, consists from an inductor, a capacitor and two rectifier diodes, connected between the input and output of the SCA. These two diodes are integrated into the SCA module.

Preferably, the SCA module contains only semiconductor components, so as to be fabricated as a monolithic integrated circuit for low power applications, or as a hybrid circuit for medium and high power applications, in both cases packaged in a three terminal or two port heat dissipating package. Using this construction, increased power handling capability is obtained. This construction also reduces the number of interconnections required for integration, as well as reducing the unit cost of mass production. Passive components required for SCA operation, like inductors and some of the capacitors, which can not be fabricated as semiconductor products are connected via suitable inlets in the SCA package in case of monolithic design, or within the module in case of hybrid design.

Preferably, the proposed construction enables separate mounting of modules and components in a manner that is optimal to heat dissipation. Interconnections between different terminals of models or components of this construction are provided using wires and/or conductive traces on a printed circuit board or on an alumina substrate, reducing the labor associated with low cost construction. The apparatus further comprises an internal power supply driven from the output voltage or from the switched voltage of the SCA module.

Brief Description of the Drawings

The above and other characteristics and advantages of the invention will be better understood through the following illustrative and none-imitative detailed description of preferred embodiments thereof, with reference to the appended drawings, wherein:

- Fig. 1 is a schematic diagram of a conventional (prior art) PWM boost converter;
- Fig. 2 is a schematic diagram of a conventional (prior art) APFC stage;
- Fig. 3 is a schematic diagram of a conventional (prior art) APFC stage in one block;
- Fig. 4 is a schematic diagram (prior art) of a control circuit of an APFC stage;
- Fig. 5 is a schematic diagram (prior art) of another control circuit of an APFC stage;
- Fig. 6 is a schematic diagram of a modular construction of an APFC stage, according to the present invention;
- Fig. 7 is a schematic diagram of a modular construction of an APFC stage, as a two-port network;
- Fig. 8 is a schematic diagram of the construction illustrated in Fig. 6, with improved heat dissipation;
- Fig. 9 is a schematic diagram of a Switch and Control Assembly (SCA), according to the present invention;
- Fig. 10 is a schematic diagram of a resonant local power supply for the SCA, according to the present invention;
- Fig. 11 is a schematic diagram of a resonant local power supply integrated into the SCA, according to the present invention;
- Fig. 12 is a schematic diagram of an SCA with a lossless snubbing circuitry, according to the present invention;

- Fig. 13 illustrates the APFC stage of Fig. 6, constructed according to the present invention, where the SCA is fabricated as a four pin IC;
- Fig. 14 illustrates the APFC stage of Fig. 7, constructed according to the present invention, where the SCA is fabricated as a five pin IC;
- Fig. 15 illustrates an APFC stage , constructed according to the present invention, where the SCA is fabricated using hybrid technology;
- Fig. 16 illustrates an APFC stage , constructed according to the present invention, where the SCA is constructed in a manner suitable for hybrid IC technology;
- Fig. 17 illustrates a full APFC stage construction according to the present invention.

Detailed Description of Preferred Embodiments

For a better understanding of the present invention, the structures of prior art are examined, according to the illustrations presented by Fig. 1 to 5. A typical prior art implementation of APFC stage, known as PWM boost converter, is shown in Fig. 1. The input AC voltage is rectified by an array **1**, of four rectifying diodes, and fed into a boost stage that comprises an input inductor **2** (L_{in}), a switch **3** (S_1), a high frequency rectifier **4** (D_2), an output filtering capacitor **5** (C_0) and a load, represented by a resistor **6** (R_L). Switch **3** is driven by a high frequency control signal with duty cycle D, such that the shape of the input current i_{in} follows the shape of the rectified input voltage V_{ivR}. Consequently, the input terminal (before the inductor 2) will have resistive characteristics, i.e., the Power Factor (PF) equals unity.

Another prior art implementation, shown in Fig. 2, comprises both passive and active components. The input AC voltage is rectified by an array **7**, of

four rectifying diodes, and fed into a boost stage that comprises an input inductor 8 (L_{in}), a power Metal Oxide Semiconductor Field Effect Transistor (MOSFET) switch 9 (Q_1), a high frequency rectifier 10 (D_2), an output filtering capacitor 11 (C_0), a load, represented by a resistor 16 (R_L), an IC Active Power Factor (APF) controller 12 with its auxiliary passive components circuit 17, a current sensing resistor 13 (R_s), a voltage sensing resistor 18 (R_{ac}),and an output voltage divider, constructed from resistors 14 (R_1) and 15 (R_2). MOSFET switch 9 is driven by a high frequency control signal from the APF controller 12. Here, some components (such as inductor 8 and capacitor 11) are of relatively large size, which is not compatible with microelectronics technology. Other silicon semiconductors, such as APF controller 12 and rectifier 10 may be fabricated on a monolithic IC chip. However, the stage of Fig. 2 still comprises many discrete components with their associated wiring, that preclude the streamlining of the APFC stage. For example, the rectified input voltage V_{ivR} should be sensed, and hence a wire should be connected between the feed point "c" and the controller 12. In order to regulate the output voltage, the voltage at point "b" (the output of the voltage divider R_1, R_2) is also sensed by the controller 12.

Another prior art, comprising a complete stage, similar to the stage of Fig. 2, (excluding the output filtering capacitor 20) packaged into one APFC block 19 is shown in Fig. 3. Here, all heat dissipating elements are in close proximity, complicating heat removal.

In an improved prior art APFC stage, illustrated in Fig. 4, comprises a modified control operation, in which sensing of the input voltage V_{ivR} is not required. The voltage V_a at point "a" is a pulsating voltage of maximum amplitude V_0 and duration of T_{OFF} when switch 21 (S_1) is not conducting. Consequently, the average voltage at point "a" v_{av} is given by:

$$v_{av} = \frac{V_o \cdot T_{OFF}}{T_s} \qquad \text{[Eq. 1]}$$

where T_s is the PWM switching period, or:

$$v_{av} = V_o \cdot D_{OFF} \qquad \text{[Eq. 2]}$$

where

$$D_{OFF} = \frac{T_{OFF}}{T_s} \qquad \text{[Eq. 3]}$$

Similarly, the "on" duty cycle D_{ON} while S_1 is conducting (a period of T_{ON}) is given by:

$$D_{ON} = \frac{T_{ON}}{T_s} \qquad \text{[Eq. 4]}$$

The input voltage V_{ivR} fed into the boost converter is assumed to be of low frequency, compared to the switching frequency f_s ($f_s=1/T_s$), and hence may be considered constant during one or several switching periods. If the power stage is properly controlled, the average low frequency voltage across inductor 22 (L_{in}) is almost zero (otherwise the current would risen to large values). Thus:

$$v_{ivR} = v_{av} \qquad \text{[Eq. 5]}$$

where v_{ivR} is the instantaneous low frequency component of V_{ivR}.

From Eq. 1 and Eq. 5, the following equality is obtained:

$$v_{ivR} = V_o \cdot D_{OFF} \qquad \text{[Eq. 6]}$$

In case when D_{OFF} is programmed according to the following rule:

$$D_{OFF} = K \cdot i_{ina} \qquad \text{[Eq. 7]}$$

where K is a constant, and i_{ina} is the low frequency component of the input current i_{in}, then:

$$v_{ivR} = V_o \cdot K \cdot i_{ina} \qquad \text{[Eq. 8]}$$

or:

$$i_{ina} = \frac{v_{ivR}}{V_o \cdot K} \qquad \text{[Eq. 9]}$$

If the filtering capacitor 23 (C_0) is sufficiently large so that the ripple of the output voltage V_0 may be neglected, then according to Eq. 9 the input

current follows the input voltage. Hence, the converter stage looks resistive with the following input resistance:

$$Re = K \cdot V_o \qquad \text{[Eq. 10]}$$

From Eq. 10, the value if the input resistance R_e as well as the input current may be controlled by adjusting the value of K. Practically, the output voltage should remain constant even for variations in the load 24 (R_L). This may be obtained by establishing a closed control loop on K. The voltage v_{iin}, which is proportional to the input current (i_{ina}) sensed by the sensing resistor 25 (R_s), is fed into a multiplier 26 (M). An error amplifier 27, compares the output voltage V_0 with a reference voltage V_{ref}, generating an error voltage V_e, which is also fed into the multiplier 26. The product $v_{iin} \cdot V_e$, which is proportional to i_{ina} by the factor K, is fed into a PWM modulator 28, which generates the duty cycle pulse (D_{OFF}) according to Eq. 7.

Another improved prior art APFC stage, illustrated in Fig. 5, exploits the current flowing in the MOSFET switch 29 to generate the duty cycle pulse (D_{OFF}). The sensing resistor 30 (R_s) is placed in series with the MOSFET switch 29, whereas the voltage across it is being used to measure the input current i_{ina}. This implementation, as well as the implementation described in Fig. 4 above, do not require input voltage sensing, lowering the number of the required interconnections.

According to one preferred embodiment of the present invention, the APFC stage comprises four basic sub-circuits, two modules and two structural elements, being connected to each other as illustrated in Fig. 6. The first module consists from a widely used input rectifier array 31 (D_1). This module has one inlet connected to the power line and one DC outlet. This inlet is normally pre-filtered by a conventional noise filter to suppress noise entering from the line. A capacitor (C_1) may be optionally connected across the rectifier array output so as to filter high frequency

components of the rectified voltage to ground. The first structural element is the input inductor **32** (L_{in}), which may tapped and may consist from additional inductor, in case when a snubber is used. This inductor is being connected between the rectifier module and the SCA module.

The second module is the Switch and Control Assembly (SCA) **33**, consists from all the semiconductor components of the switching, control, rectifier and power supply circuitry. The inlet of this module is being connected to the output of the first module **31** via the input inductor **32** (L_{in}), and the outlet to the load. The SCA module may optionally comprise a turn-on snubber. According to the invention, the SCA module may have three terminals, one for input, one for output and one for ground.

The second structural element is the output capacitor **34** (C_0), being connected across the outlet of the SCA, in parallel with the load. This modular construction is simpler than prior art implementations, with very few interconnections and with a simple forward flow of power and signals. In addition, the physical location of the three power dissipating elements, the input rectifier array **31** (D_1), the input inductor **32** (L_{in}), and the SCA **33** is not critical, so they may be mounted separately, with the best possible heat removal.

Fig. 7 illustrates a different construction, according to another preferred embodiment of the present invention. In this implementation, SCA **35** is connected to the same construction described if Fig. 6 above, but as a two port network. This construction provides sensing of the input current within the SCA, thereby simplifying the control circuitry.

According to another preferred embodiment of the present invention, the high frequency output rectifier diode **36** (D_2) is separated from SCA **37**, as shown in Fig. 8. This construction allows better cooling and mounting.

The SCA may by realized differently with respect to its internal circuitry, packaging and production technology. Fig. 9 illustrates a typical realization of an SCA circuitry, according to the invention, where all microelectronics compatible components are grouped together. The internal power supply (V_{CC}) required for SCA operation may be obtained from the output voltage using an auxiliary circuit, which comprises a current source **38** (I_{aux}), a zener diode **39** (Dz_{aux}) for power supply stabilization, and a smoothing capacitor **40** (C_{aux}). In case of high power applications, the smoothing capacitor **40** (C_{aux}) may be an electrolytic capacitor located outside the SCA module. This SCA implementation employs a typical PWM modulator, controlled by a control circuit as described above with reference to Fig. 4.

According to the invention, a different internal power supply for high power modules is constructed, as shown in Fig. 10. A charge pump capacitor (C_x) is connected in series with the positive terminal of the pulsating voltage, which may be the drain of the switching transistor. A rectifying diode (D_x) is connected in series with the output of the charge pump capacitor. A zener diode (D_{Zaux}) for power supply output voltage stabilization is connected between the rectifier diode (D_x) and ground. A smoothing capacitor (C_{aux}) is connected in parallel with the zener diode (D_{Zaux}). An inductor (L_x) is connected in series with another rectifier diode (D_{x1}), between the second terminal of the charge pump capacitor (C_x) and ground.

According to one preferred embodiment of the invention, power supply output voltage is stabilized by a fixed or adjustable voltage regulator, instead of using the zener diode Dz_{aux}. This voltage regulator provides better ripple rejection at the output. The voltage regulator input is connected to the cathode of the rectifying diode D_x, the common terminal

is connected to ground and the power supply output voltage is taken from the voltage regulator output, filtered by the smoothing capacitor C_{aux}.

The input of the internal power supply circuit may be connected to a pulsating source (V_{pulse}), such as the voltage V_a defined in Fig. 4 above. For each rising edge of the square-wave input, the charge pump capacitor 41 (C_x) delivers a constant charge, Q_{x1}, to the output Vcc, which is given by:

$$Q_{x1} = V_p \cdot C_x \qquad \text{[Eq. 11]}$$

where V_p is the magnitude of V_{pulse} and C_x is the capacitance of capacitor 41. Thus, for a switching frequency of f_s, the current I_{CC1}, fed into Vcc terminal by the discrete charges Q_{x1} is given by:

$$I_{CC1} = V_p \cdot C_x \cdot f_s \qquad \text{[Eq. 12]}$$

C_x is charged to the voltage V_p - Vcc, according to the charge transfer. When V_{pulse} becomes zero, the charge pump capacitor 41 (C_x) together with the inductor 42 (L_x) form a resonant circuit, which charges capacitor 41 (C_x) until the voltage across it reaches -Vcc. At that moment, the current of inductor 42 (L_x) flows into Vcc terminal until the current decays to zero. The energy transferred from capacitor 41 (C_x) to Vcc is given by:

$$Ecc2 = \frac{(Vp - Vcc)^2 - Vcc^2}{2} \cdot Cx \qquad \text{[Eq. 13]}$$

and the current I_{CC2} delivered to Vcc is given by:

$$Icc2 = \frac{(Vp - Vcc)^2 - Vcc^2}{2 \cdot Vcc} \cdot Cx \cdot fs \qquad \text{[Eq. 14]}$$

From Eq. 13 and 14, the total current Icc flowing into Vcc is given by:

$$Icc = Icc1 + Icc2 = \left\{ Vp \cdot Cx + \frac{(Vp - Vcc)^2 - Vcc^2}{2 \cdot Vcc} \cdot Cx \right\} \cdot fs \qquad \text{[Eq. 15]}$$

The SCA resonant power supply described in Fig. 10, is of high efficiency, since most of the energy flowing in its reactive elements is recovered.

Fig. 11 illustrates an integration of the resonant power supply described in Fig. 10 into the SCA module, according to a prefferred embodiment of the invention. Such integration improves the operation of the boost power stage, by providing a "soft switching" to switch 43 (S_1). Capacitor 44 (C_x) functions as a turn-off snubber for the switch, by slowing the rate of voltage developed across the switch. The overlapping time, when both voltage across the switch, and current through the switch are present, is reduced, reducing the switching losses. Moreover, since capacitor 44 (C_x) is charged (and discharged) by a current source (which is actually the inductor L_{in} in Fig. 1), the charging (and discharging) process is almost lossless, resulting in an improved efficiency.

According to another preferred embodiment of the present invention, a further improved APFC stage may be constructed, by adding a turn-on snubber to the circuit. This approach is illustrated in Fig. 12. The tapped inductor 45 (L_{in}), diodes 46 (Ds_1) and 47 (Ds_2), together with snubber elements (inductor 48 [L_r], and capacitor 49 [C_r]) reduce the switching losses during turn-on time. Still, the modular design presented in the invention is retained, even after adding the described snubbing circuitry or any other snubbing circuitry.

Production concept of SCA modules may vary according to the required quantities and power levels. Fig. 13 illustrates a construction of the APFC stage described in Fig. 6 above, according to a preferred embodiment of the invention. The SCA module is fabricated as a monolithic (chip) IC, packaged in a four pin package 50. This construction is suitable mainly for low power applications.

Fig. 14 illustrates construction of the APFC stage described in Fig. 7 above, according to another preferred embodiment of the invention. Here too, the SCA module is fabricated as a monolithic (chip) IC, packaged in a

five pin package 51. This construction as well, is suitable mainly for low power applications.

Fig. 15 illustrates construction of the APFC stage, according to another preferred embodiment of the invention. The SCA module is fabricated as a multi-chip hybrid circuit, packaged in a three pin package 52, with an associate Printed Circuit Board (PCB) based sub-assembly 53. This construction is suitable mainly for medium and high power applications.

In case when the user prefers to use an (already) available power supply, an extra pin for external power supply may be easily provided, as shown in Fig. 13 and 14 above. However, the main feature is related to minimal number of interconnections between the SCA module and other components.

Example 1

Fig. 16 is a complete schematic diagram of an APFC stage structure, where the SCA module 78 includes internal power supply and turn-on snubber circuits, according to the invention, and is fabricated as a multi-chip hybrid circuit. The rectifier array is contained in a separate module 60. The input inductor 61 (L_{in}), which in this case is a tapped inductor, as well as the snubbing circuit inductor 62 (L_r), and the snubbing circuit capacitor 64 (C_r) are excluded from the SCA module, since they are not compatible with IC or hybrid technology. The control circuit controlling the switching transistor 77 (Q_1) is implemented using IC components. The voltage V_{ref} is generated from V_{CC} by a resistor R_2 and a zener diode D_{z2}, feeding the error amplifier 68 (U_3). The resulting error is fed into the multiplier 72 (U_4) together with the voltage across the sampling resistor 71 (R_s). The output voltage V_m from the multiplier is fed into comparator 66 (U_1), together with a ramp voltage V_{ramp}, which varies

between a peak value of V_p and zero, thereby determining the switching frequency f_s ($f_s=1/T_s$).

The peak value of the ramp voltage V_p is determined from V_{CC} by resistor **75** (R_s) and zener diode **76** (D_{z1}). A current source **65** (U_5) charges the capacitor **69** (C_{ramp}) to V_{ramp}. V_{ramp} is fed together with V_p into another comparator **67** (U_2), which discharges C_{ramp} by driving transistor **70** (Q_2) for a short determined period whenever V_{ramp} exceeds V_m. In this way, the time T_{off} during which the switching transistor **77** (Q_1) is not conducting, is proportional to V_m, and hence, to the input current i_{ina} (using Eq. 7 above). Using this construction, all the elements within the SCA module **78**, ICs, semiconductors, resistors, capacitors and inductor **63** (L_x) may be integrated into one hybrid circuit.

Example 2

A full APFC stage construction presented by Fig. 16 is illustrated in Fig. 17. Both rectifier array **80**, and SCA **84** modules are ICs and/or hybrid circuits, packaged each in a heat dissipating package (Alumina, for instance) with metallic leads, and mounted on heat-sink **90** by drilling suitable holes **81** and **92** in the PCB **89**, respectively, by gluing with heat conductive adhesive or soldering. The PCB **89** is mounted to the case by using screw(s) **91**, or by soldering.

Printed copper traces **88** are used to connect between terminals of different components. The input tapped inductor **82** (L_{in}), the snubber inductor **83** (L_r), the snubber capacitor **86** (C_r), and the output capacitor **87** (C_o), are glued or soldered on the PCB material. Capacitor **93** (C_1) used for filtering high frequency components of the rectified voltage is optionally connected across the rectifier array **80** output. Each terminal of these components is soldered to a corresponding copper pad on the PCB.

Of course, the above examples and description has been provided only for the purpose of illustrations, and are not intended to limit the invention in any way. As will be appreciated by the skilled person, the invention can be carried out in a great variety of ways, employing more than one technique from those described above, all without exceeding the scope of the invention.

CLAIMS

1. Modular apparatus for regulating the harmonics of current drawn from power lines by electric equipment, comprising:

a) a first rectifier circuit module, comprising an array of rectifying diodes;

b) a second Switch and Controller Assembly (SCA) module, comprising a power switch and controller and their interconnections;

c) at least one input inductor, filtering the current drawn from the rectifier module; and

d) at least one output capacitor, filtering the output voltage ripple at the load.

2. Apparatus according to claim 1, further comprising:

a) a connection between the inlet of the rectifier and the power line;

b) a connection between an outlet of said rectifier module and the SCA;

c) a connection between the inlet of said SCA and said rectifier, via an inductor;

d) a connection between the outlet of said SCA and the output capacitor;

e) a connection between the inlet of the inductor and said rectifier;

f) a connection between the outlet of the inductor and the inlet of said SCA; and

g) a parallel connection between the capacitor and the load.

3. Apparatus according to claim 1, wherein the SCA comprises:

a) a switching transistor connected in parallel with the SCA inlet;

b) a high frequency rectifier diode connected in series with the SCA outlet;

c) a current sampling resistor in series with the SCA inlet; and

d) a control circuit controlling the switching transistor, one inlet of said control circuit being connected to the sampling resistor and the other inlet being connected with the SCA outlet.

4. Apparatus according to claim 2, wherein a turn-on snubber for soft switching is connected to the switching and control circuit assembly, the inlet and outlet of said snubber being connected to the input ant output of the SCA, respectively.

5. Apparatus according to claim 4, wherein the snubber comprises:

a) two rectifier diodes connected between a tap of the input inductor and the output;

b) an inductor connected in series with the SCA inlet; and

c) a capacitor connected between the SCA inlet and the common terminal between the two rectifier diodes.

6. Apparatus according to claims 4 and 5, wherein the two rectifier diodes of the snubber being integrated into the SCA module.

7. Apparatus according to claim 2, wherein the control circuit comprises:

a) a reference voltage source;

b) a pulse width modulator fed by a multiplier, said pulse width modulator being connected to the gate of the switching transistor controlling the switching duty cycle according to the multiplier output;

c) a multiplier being fed by the error voltage and the voltage across the input current sampling resistor; and

d) an amplifier being connected to the output voltage and the reference voltage, said amplifier feeding the multiplier with an

error voltage proportional to the difference between the output voltage and the reference voltage;

8. Apparatus according to claim 3, wherein the SCA contains an internal power supply circuit for the control circuit.

9. Apparatus according to claim 3, wherein an external power supply for the control circuit is connected to the SCA, via an inlet thereto.

10. Apparatus according to claim 2, wherein the switching and control assembly module is implemented as a three terminal unit, comprising one input, one output and one common terminal.

11. Apparatus according to claim 2, wherein the switching and control assembly module is implemented as a four terminal two port unit, comprising one input port and one output port.

12. Apparatus according to claims 7 to 11, wherein only semiconductor components are contained within the switching and control assembly module , said module being fabricated as a monolithic integrated circuit.

13. Apparatus according to claims 7 to 11, wherein switching and control assembly module being fabricated as a multi-chip hybrid circuit. thereby increasing the power handling capability.

14. Apparatus according to claims 12 and 13, wherein the switching and control assembly monolithic integrated circuit being packaged in a package suitable for connection to other units.

15. Apparatus according to claim 14, wherein the package is high heat dissipating package.

16. Apparatus according to claim 1, wherein the two modules are mounted separately in a manner enabling increased heat dissipation, thereby increasing the regulated power handling of the apparatus.

17. Apparatus according to claims 2, wherein the high frequency rectifying diode is excluded from the third module, mounted separately on a heat-sink in a manner enabling increased heat dissipation, thereby further increasing the regulated power handling of the apparatus.

18. Apparatus according to claim 8, wherein the power supply is fed from the output voltage, comprising:

a) a current source, connected to the output voltage terminal;

b) a zener diode, fed by the current source of step a) above; and

c) a smoothing capacitor, connected in parallel with the zener diode of step b) above.

19. A resonant local power supply, fed from a pulsating voltage, comprising:

a) a charge pump capacitor, one terminal of said capacitor being connected in series with the positive terminal of the pulsating voltage;

b) a rectifying diode, the anode of said diode being connected in series with the output of the charge pump capacitor of step a) above;

c) a voltage regulating device for power supply output voltage stabilization, the inlet of said voltage regulating device being connected to the cathode of the rectifying diode of step b) above, the outlet of said voltage regulating device being connected to the power supply output voltage terminal, the common terminal of said voltage regulating device being connected to the negative terminal of the pulsating voltage;

d) a smoothing capacitor, said capacitor is connected in parallel with the output of the voltage regulating device of step c) above;
e) an inductor, one terminal of said inductor being connected to the second terminal of the charge pump capacitor of step a) above, said inductor in series with said charge pump capacitor forming a resonant circuit, said resonant circuit charging said charge pump capacitor; and
f) a rectifying diode, the cathode of said diode being connected to the other terminal of the inductor of step e) above, the anode of said diode being connected to the negative terminal of the pulsating voltage.

20. A resonant local power supply according to claim 19, wherein the voltage regulating device is a zener diode.

21. A resonant local power supply according to claim 19, wherein the voltage regulating device is a fixed voltage regulator.

22. A resonant local power supply according to claim 19, wherein the voltage regulating device is an adjustable voltage regulator.

23. Apparatus according to claims 1 and 2, wherein a capacitor for filtering high frequency components is optionally connected across the outlet of the rectifier circuit module outlet.

24. Apparatus according to claim 2, wherein any required electrical connection between terminals of modules and terminals of structural components or of other modules are connected using suitable wires and/or suitable printed circuit boards.

25. Apparatus for regulating the harmonics of current drawn from power lines by electric equipment, substantially as described and illustrated.

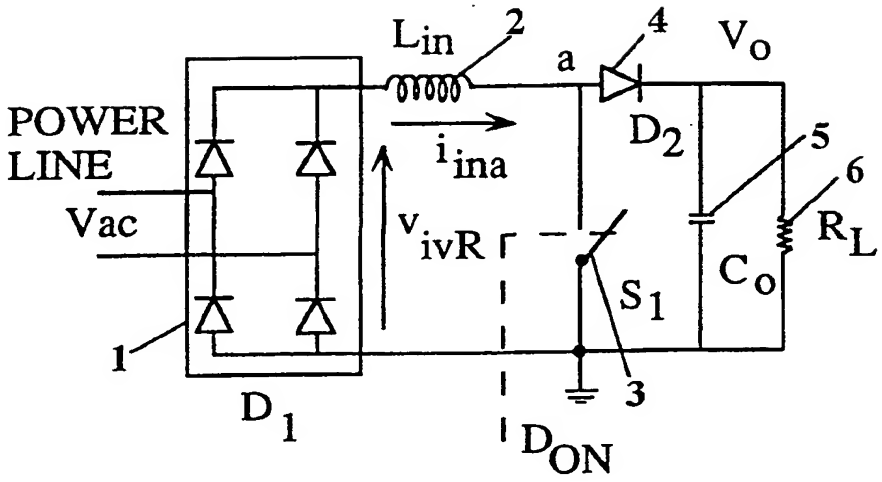

Fig. 1(prior art)

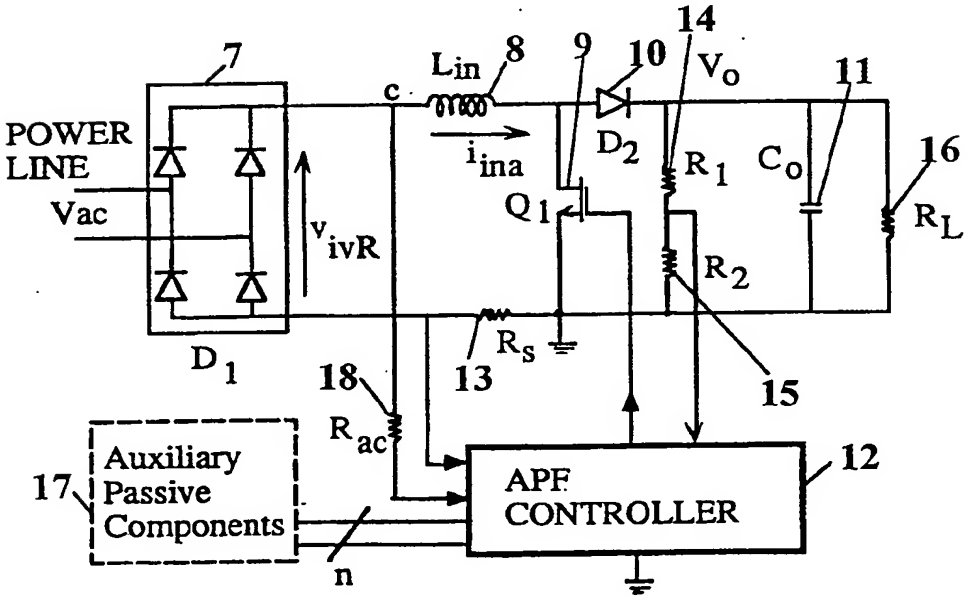

Fig. 2(prior art)

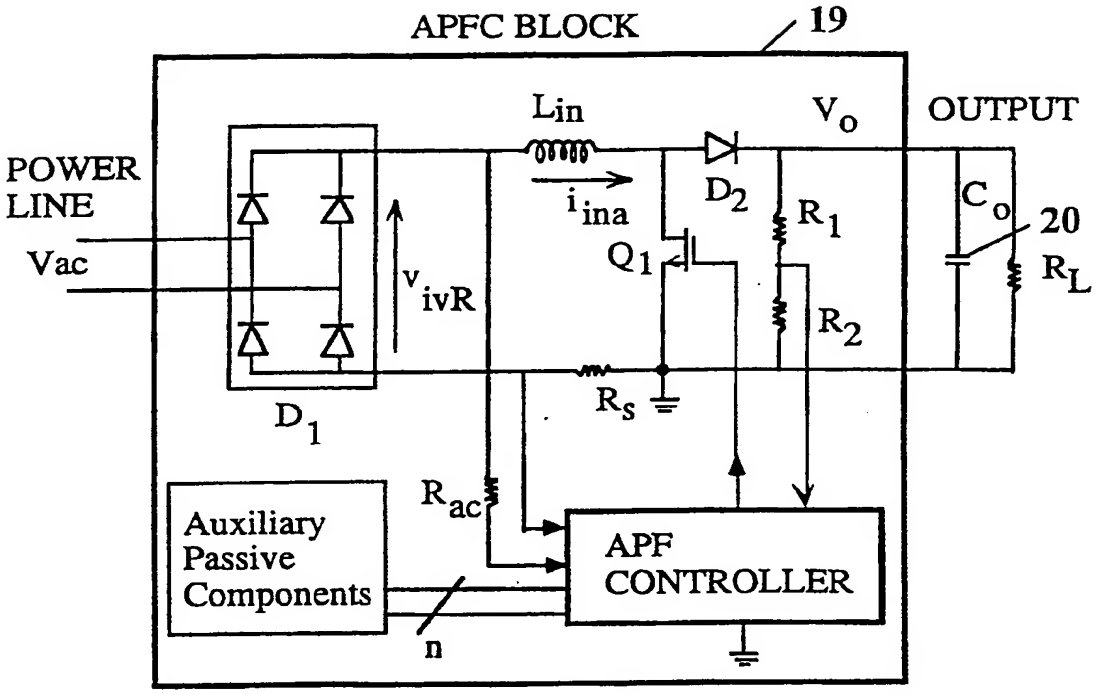

Fig. 3(prior art)

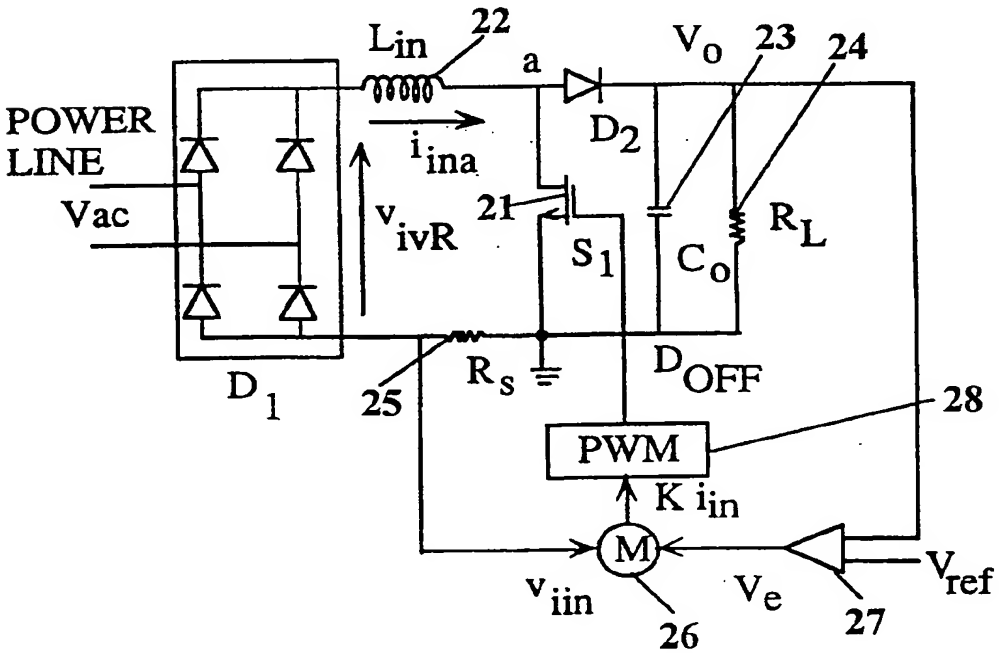

Fig. 4(prior art)

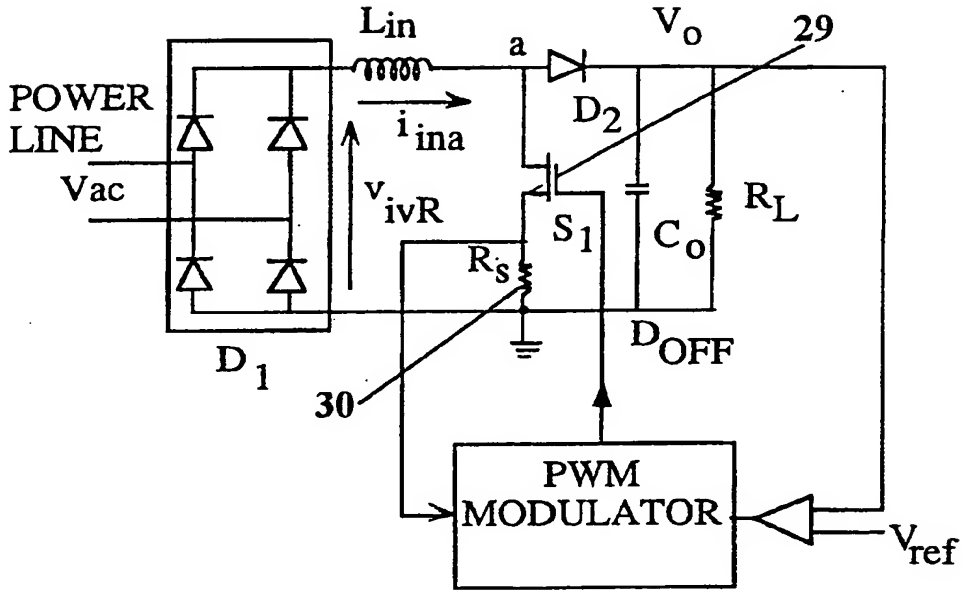

Fig. 5(prior art)

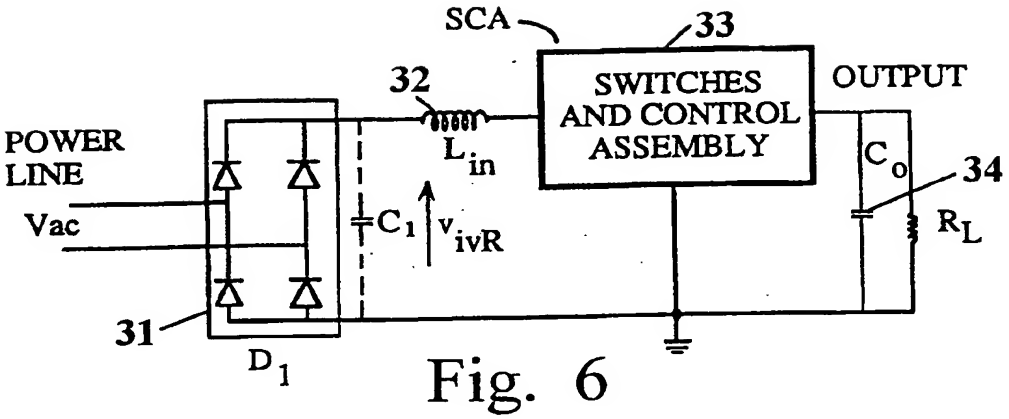

Fig. 6

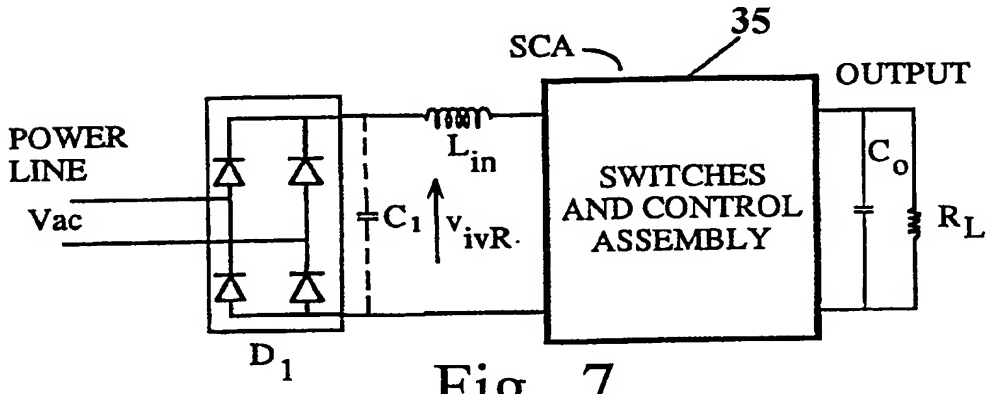

Fig. 7

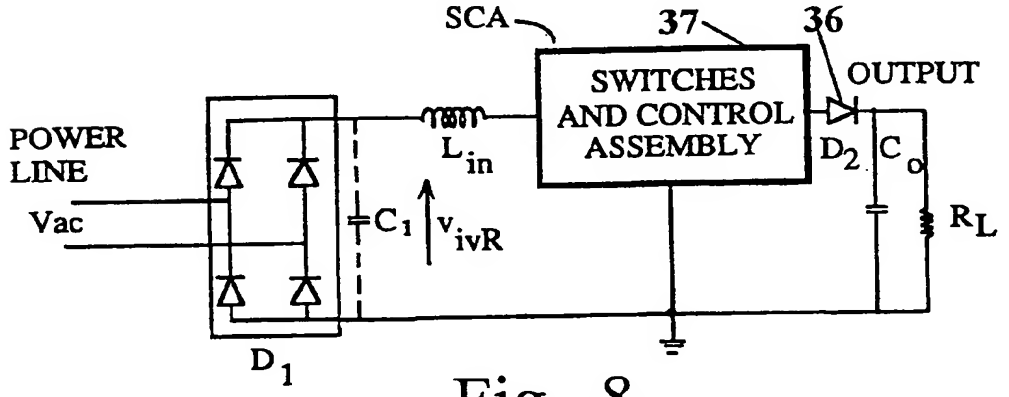

Fig. 8

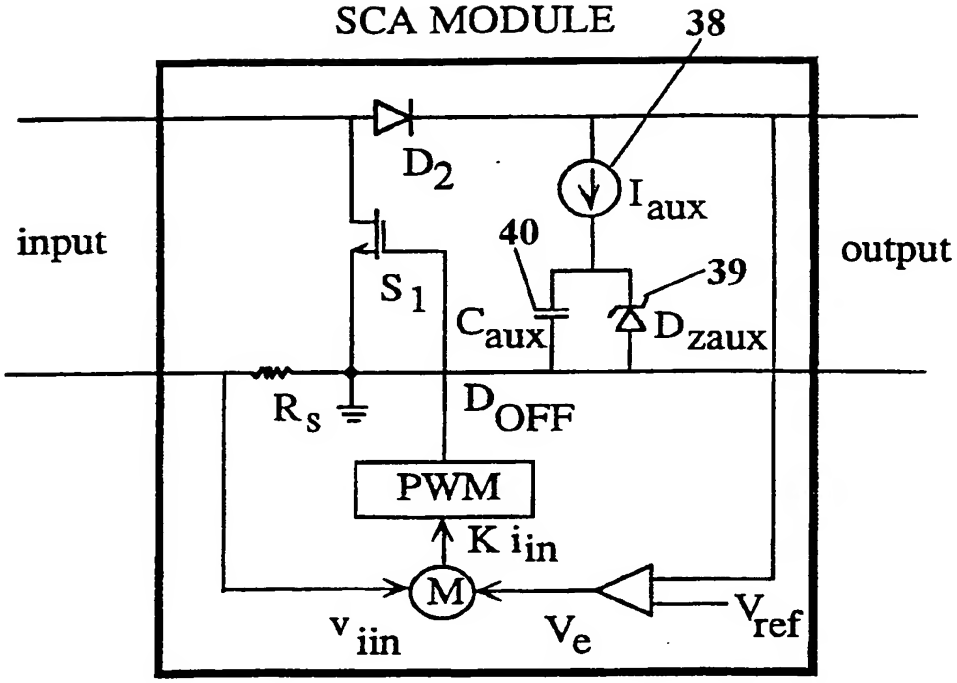
SCA MODULE
38
D2
Iaux
input
40
39
output
S1
Caux
Dzaux
Rs
DOFF
PWM
K iin
M
Vref
viin
Ve

Fig. 9

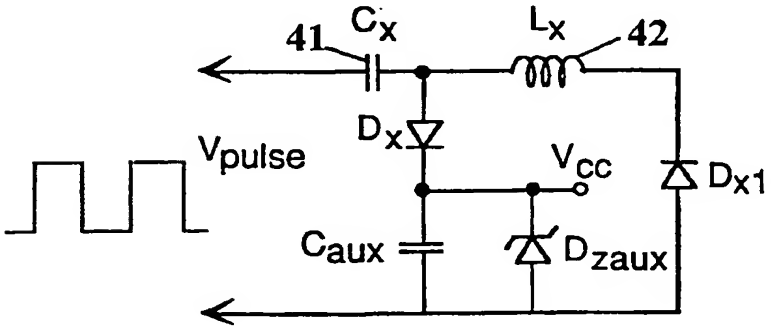
41
Cx
Lx
42
Dx
Vpulse
Vcc
Dx1
Caux
Dzaux

Fig. 10

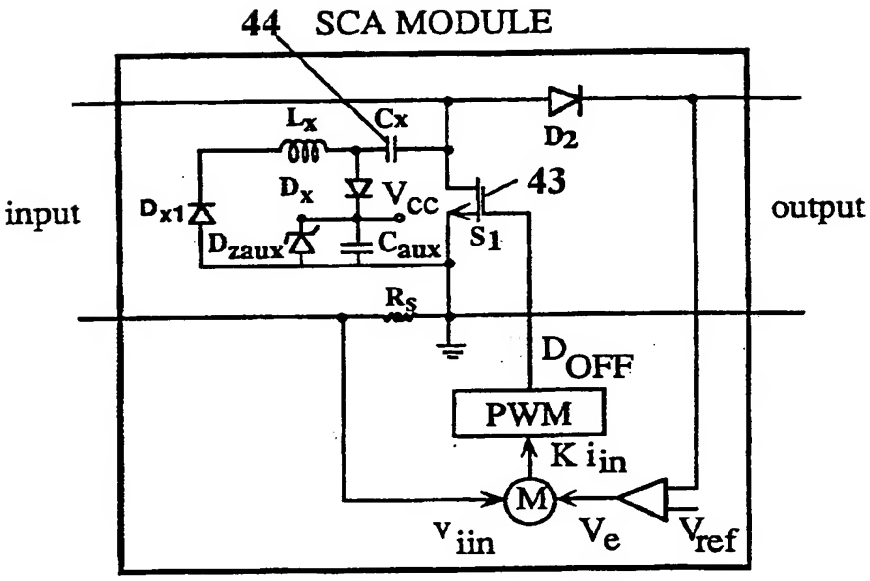
44 SCA MODULE
input
output
L_x
Cx
D_2
D_x
V_{cc}
43
D_{x1}
D_{zaux}
C_{aux}
S_1
R_S
D_{OFF}
PWM
K i_{in}
M
v_{iin}
V_e
V_{ref}

Fig. 11

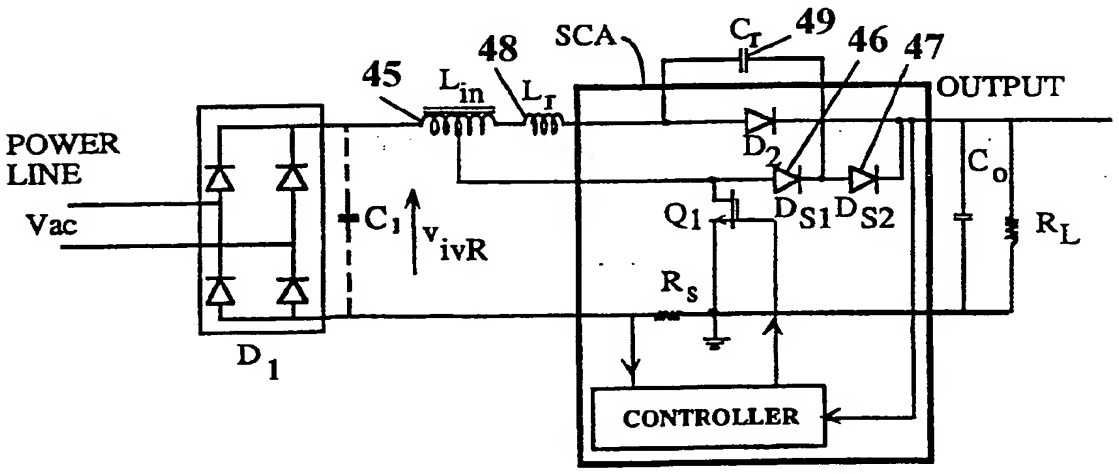
SCA
C_r
49
46
47
48
45
L_{in}
L_r
OUTPUT
POWER LINE
Vac
C_1
v_{ivR}
D_2
C_o
Q_1
D_{S1}
D_{S2}
R_L
R_S
D_1
CONTROLLER

Fig. 12

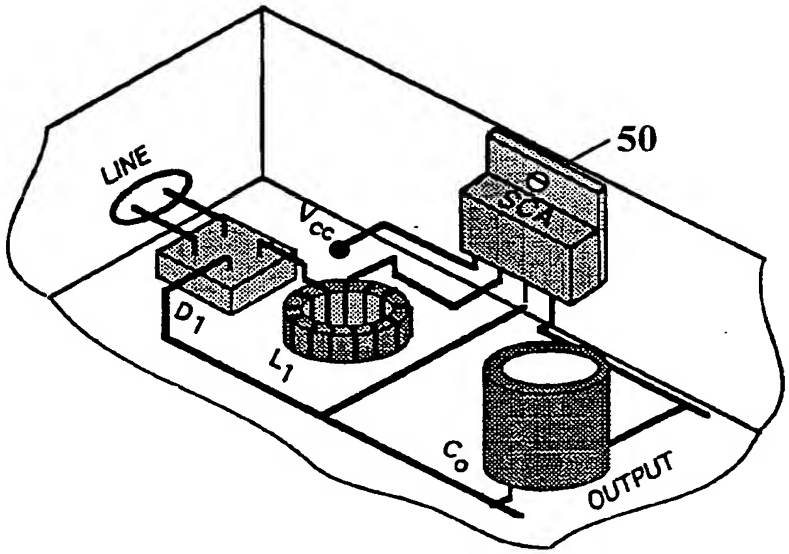

Fig. 13

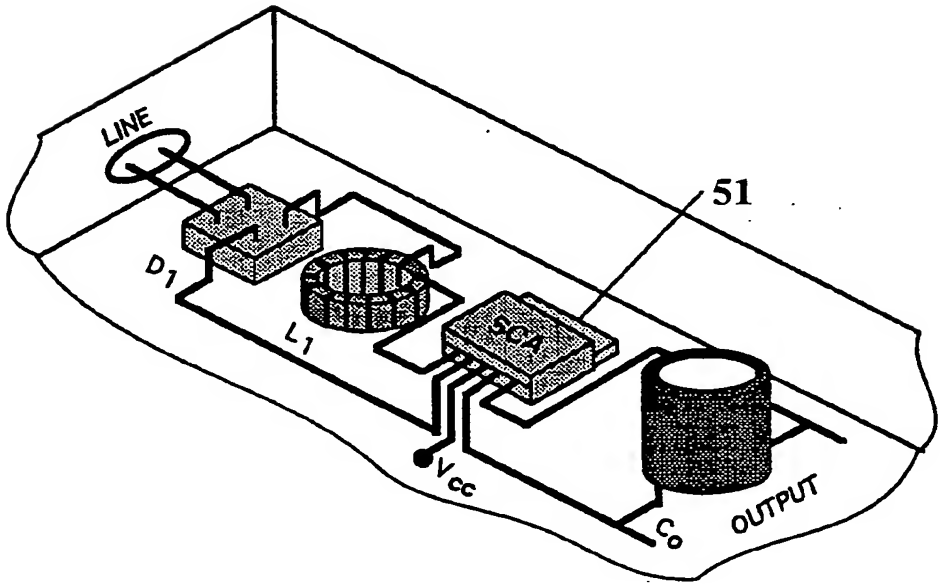

Fig. 14

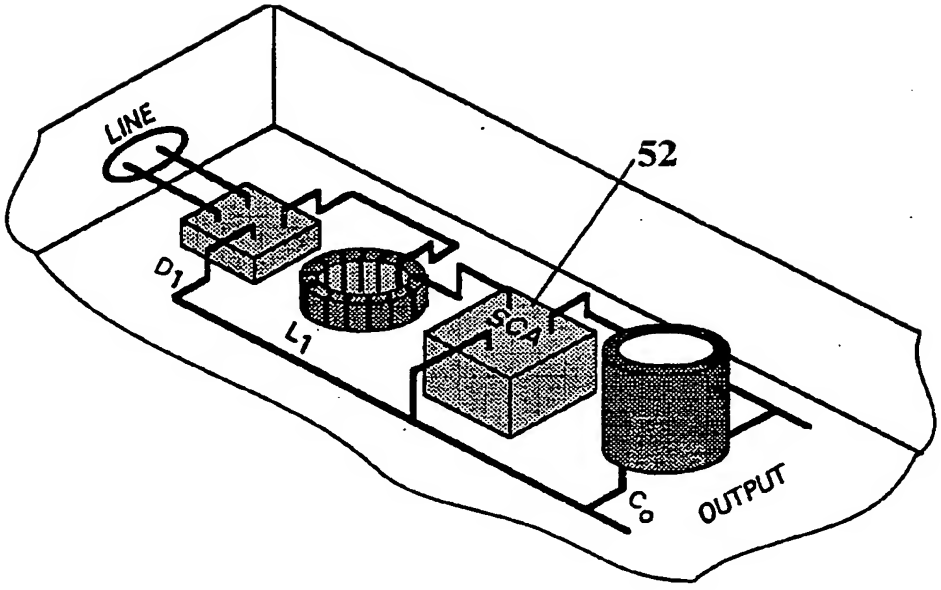

Fig. 15

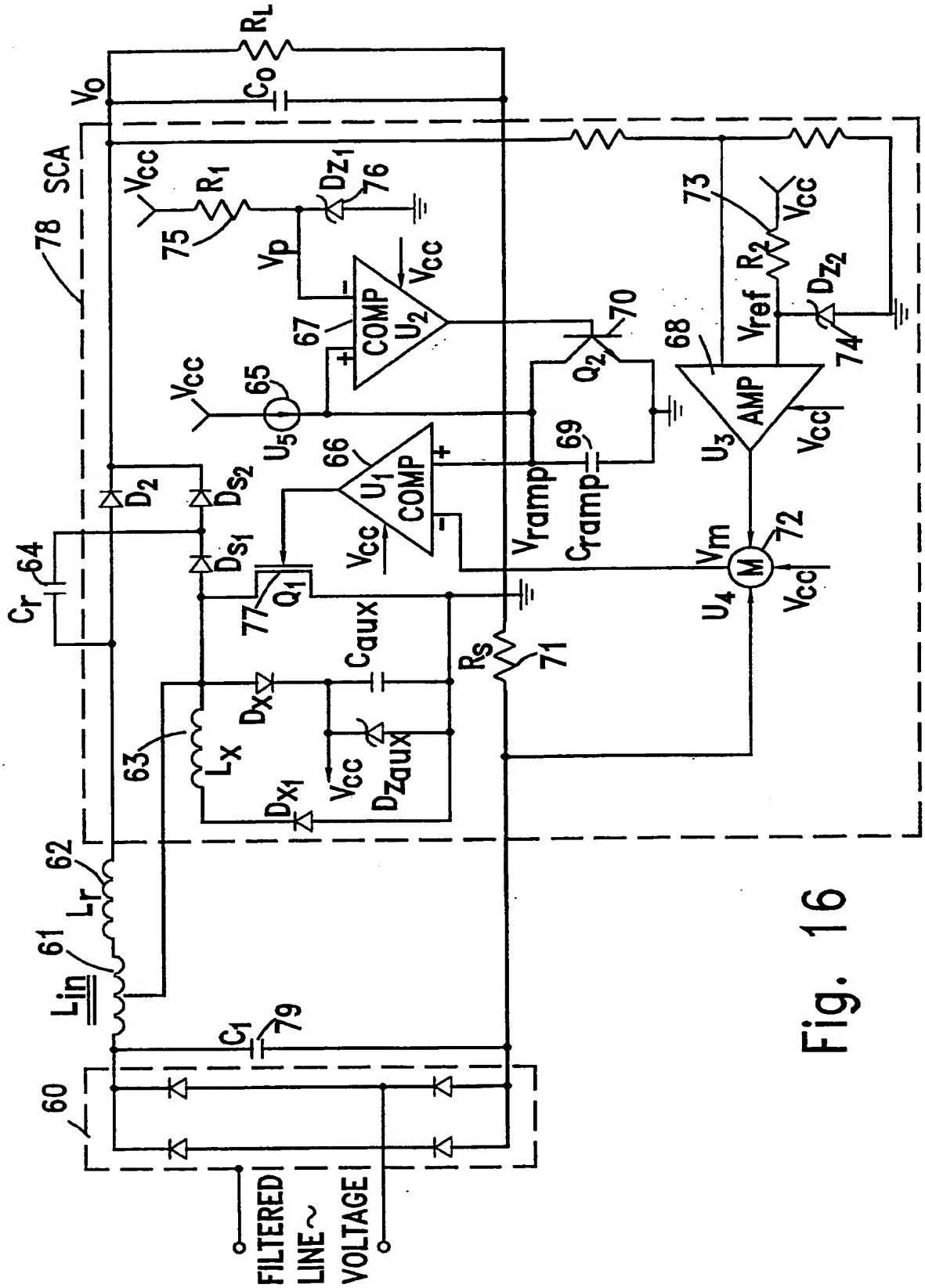
R_L
C_o
V_o
SCA
78
V_{cc}
R_1
Dz_1
76
75
V_p
67
COMP
U_2
V_{cc}
70
Q_2
73
V_{cc}
R_2
V_{ref}
Dz_2
74
68
AMP
U_3
V_{cc}
V_{cc}
65
U_5
66
U_1
COMP
69
V_{ramp}
C_{ramp}
D_2
D_{s2}
D_{s1}
V_{cc}
V_m
72
M
U_4
V_{cc}
64
C_r
77
Q_1
C_{aux}
R_s
71
D_x
63
L_x
V_{cc}
D_{zaux}
D_{x1}
62
L_r
61
L_{in}
C_1
79
60
FILTERED LINE~ VOLTAGE

Fig. 16

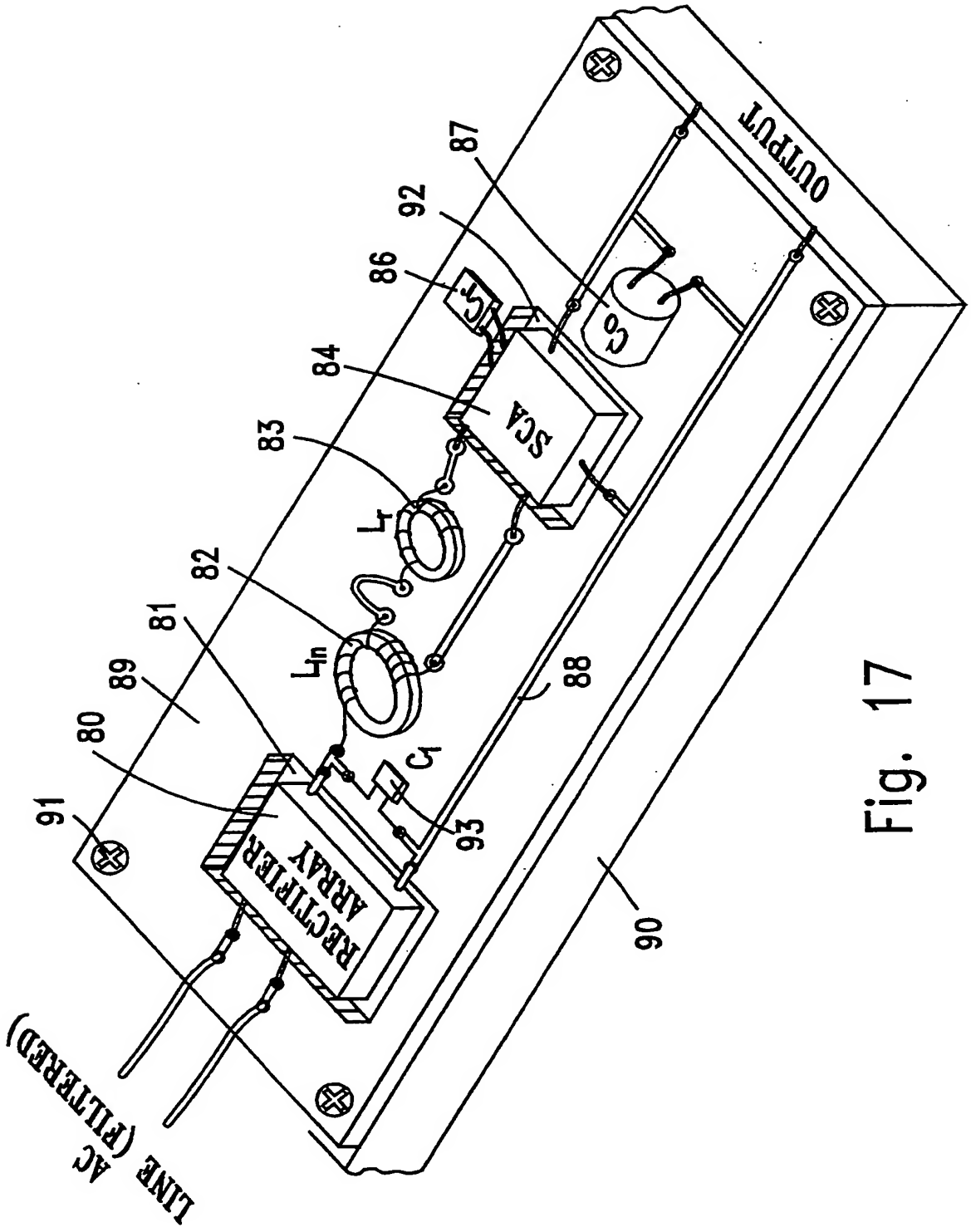
OUTPUT
87
92
86
84
83
82
81
89
80
91
88
90
93
SCA
RECTIFIER ARRAY
AC LINE (FILTERED)

Fig. 17